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GOVERNING OF WATER POWER UNDER  
VARIABLE LOADS

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## WITH DISCUSSION.

The government of water power under variable loads has always been considered a difficult problem under the most favorable conditions. Many operators of water-power plants where changes in load are great and sudden have found their government so uncertain and near the danger line that it was believed a few years ago that small electric street railway plants could not be successfully operated by water power. With large plants the change in load represents but a small percentage of the whole power in use, so that the variation in load is not so extreme as to cause serious difficulty in the government of the power. It is the extreme and sudden changes that cause trouble.

The modern ball governor, as used to regulate water-wheels, is satisfactory in its operation where the power used is fairly constant, but becomes entirely inadequate for the government of water power where

the changes of load are sudden and extreme. The author had this problem of the government of water power brought to his attention a few years ago and found little published data to assist him in solving it. The solution became a matter of experiment. The result of these experiments and the conclusions drawn from the investigation may be of some interest to the engineering profession.

The power to be governed consisted of a pair of 22½-in. Victor turbine wheels working under 40 ft. head. These wheels generated about 400 H.-P. on the wheel shaft, which is used in operating 6 miles of electric street railway, having a twenty-minute service. On this line are employed from four to ten cars daily, equipped with two 15 H.-P. single motors. The extremes of variable load are of daily occurrence. There are moments when with four or more cars in service the load is suddenly removed by the stopping of all cars at once, making a sudden change from a load of 120 H.-P. or more to no load on the generators.

This was the cause of frequent annoyance and expense due to the burning out of armatures, as the ball governor of the water-wheels does not act quickly enough to prevent racing of the wheels at times. A large fly-wheel roped with five 2-in. diameter ropes from the wheel shaft failed to hold the wheels always in check. When the wheel governor, assisted by the balance wheel, succeeded in checking the speed, as frequently occurred, the recovery of the necessary power to operate the entire load was necessarily slow in action, causing delay in the starting of the cars. These results are too well known to those who have had any experience in trying to operate a water power under extreme variable loads to need further notice. The water to operate the wheels mentioned is conducted from the head-works at the dam to the wheels through a penstock 9 ft. in diameter and 400 ft. long. The absence of a vent or standpipe on the penstock made the problem of government of the power still more difficult of solution. It has been the practice among hydraulic engineers, so far as the author is aware, to disregard length in penstocks in designing water-power plants. From the author's observation and experience it is shown that the shorter the column of water in the penstock, the easier it can be regulated or governed in flow at the wheel. In other words, in reducing the time of getting power from the water to a minimum where long penstocks are indispensable, it will add greatly to the facility of gov-

erning the water if a standpipe is placed on the penstock near the wheels to be governed, of a diameter equal, or nearly so, to that of the penstock. The vent pipes as generally used on such penstocks are entirely too small to be of any material service in governing the water power developed. It is readily understood that when the velocity of flow of the water in a long penstock is checked, time is required for the same velocity to be again acquired. The standpipe suggested for such cases acts as a governor and brings the actual head of water into effect in the minimum period of time. It acts as a reserve force to allow the water in the penstock to regain the required velocity.

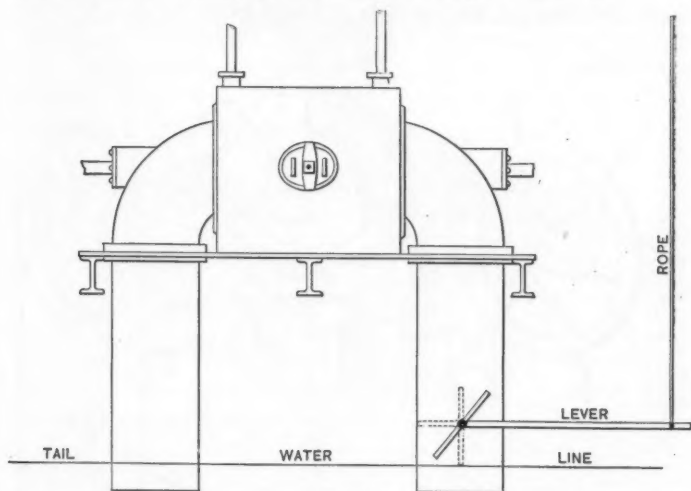


FIG. 1.

The power company had under consideration several electrical devices for relieving the machines of surplus current, but these were abandoned, either as being too expensive to be considered or as being insufficient in operation. A patented electric governor was obtained and has now been in operation for about two years and has proved successful beyond all expectations.

The governor was placed in position under a guarantee from the inventor to accomplish certain results or receive no compensation for the governor. He failed to accomplish the promised conditions, but the result was so highly satisfactory and such an improvement over

anything before tried that the company gladly paid for the governor. Some minor improvements since made have brought it up to the promised efficiency.

The electric governor consists of a gate regulator, a high-speed engine regulator and a common telegraph or gravity battery, with its

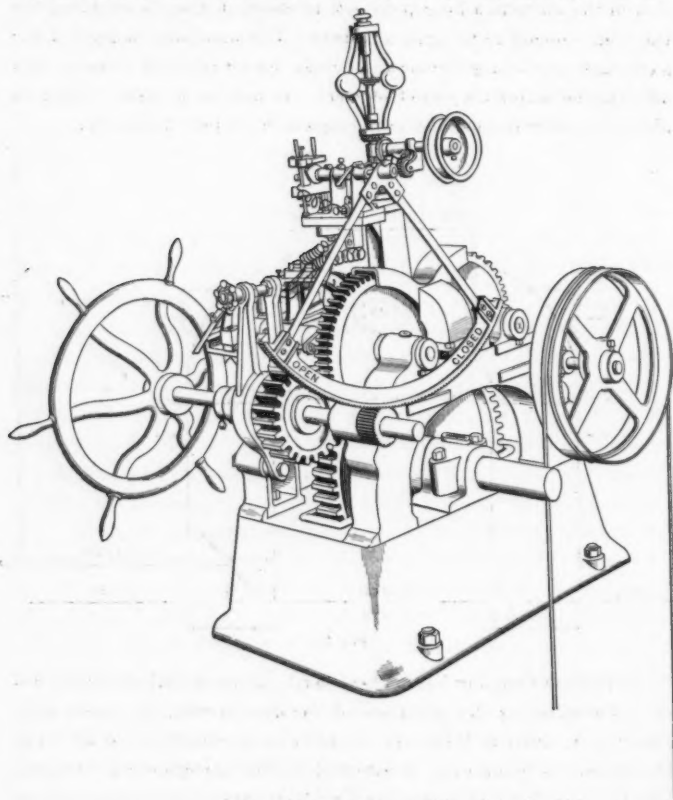


FIG. 2.

circuit. The regulator is powerful enough to control the wheel gates, and receives its power directly from the wheels. It is also so sensitive that the battery current will cause it to move the gates as desired. The engine governor is simply used as an indicator of speed, and as the indicator rises or falls it makes an electric contact, tele-

graphing the regulator which way to move the gate. There is no limit to the distance that may be between engine governor and gate regulator. Fig. 1 is a cut of the governing gate in use. This gate is placed in the draft tube, and is known as a butterfly or damper gate. To the gate axis, extending through the draft tube, is attached a lever, worked by means of a wire rope attached to a pulley on the regulator, the gate being opened or closed as the speed of the regulator increases or diminishes, the register gate of the turbines being left wide open constantly while the wheels are in operation. Fig. 2 is a general cut of the governor. The wire rope passes several times around the pulley shown on the right of the cut, one end of the rope

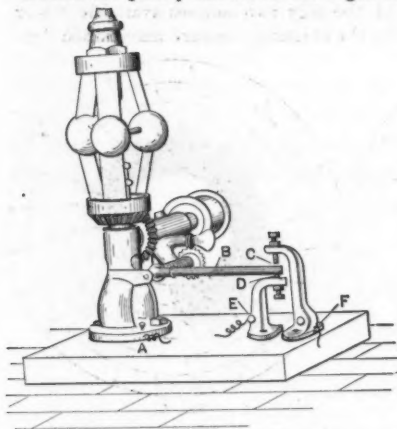


FIG. 3.

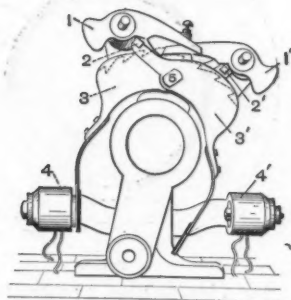


FIG. 4.

being attached to the lever of the gate in the draft tube, and the other end to a counter-balance weight. The end to which the counter-weight is attached was formerly made fast to the pulley. The substituting of a counter-weight for this arrangement is advisable, as it is a help to quick action, and relieves the machines of an unnecessary load in closing the gate.

Figs. 3 and 4 show the electrical connections of the speed governor and regulator pawls. The speed governor is belted to the shaft to be regulated, and a rise or fall in the speed of the shaft causes a corresponding rise or fall in the little lever B. The lever B is a portion of the battery circuit, and in falling makes or completes the circuit at

the contact *D*, which is connected by wire to magnet 4. Magnet 4 becomes energized and attracts armature 3, lowering lug 2, which action permits gravity to drop pawl 1 into the ratchet shown in dotted lines. The motion of the ratchet wheel opens the gates. This operation is instantaneous, and gives to gravity the advantage of time that is lost in the heavy slow-acting balls which must necessarily be used in mechanical water-wheel governors. A reverse of this process will close the gate.

"Gravity is the force from which we derive energy in water power. The energizing effect is constant as far as pressure is concerned. If more power is required from a water-wheel at any time it must necessarily come from one or both of the only two sources available under the existing conditions, namely, the existing pressure maintained dur-

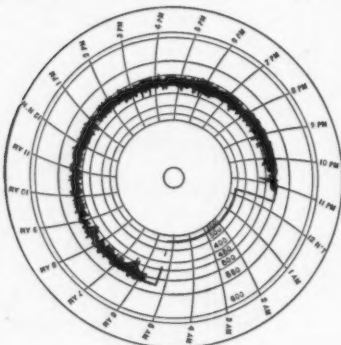


FIG. 5.

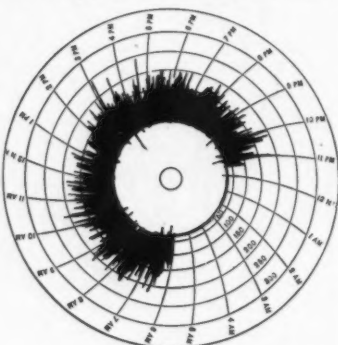


FIG. 6.

ing a longer time, or a greater area of pressure during the same time. Since it is impossible to maintain an even speed for fluctuating loads by the former source, we must resort to the latter. And since it requires time for gravity to energize or give motion to the increased quantity of water required for an increase of load, it is evident that most valuable time can be saved by opening the gates at the earliest possible indication of decrease of speed."

The foregoing in the language of the inventor correctly asserts the principle upon which this governor is constructed. He accomplishes this result by an extremely sensitive governor, the sole duty of which is to indicate variations of speed. The battery power serves simply to trip the pawls which throw the gate mechanism into action. Fig. 5 is an average voltage card for a day's run on the electric street railway. It is taken at random from the daily cards taken at the power

station. Fig. 6 is the recorded amperage for same day. These records do not fall much below the average records of the best governed engine work. This governor, as will be seen from the description, is not an expensive piece of mechanism. Its construction is simple. The expense of maintenance for the time it has been in service under the author's observation consists of the occasional renewal of the wire rope. While the author is not prepared to say that this is the best device on the market for the government of water power under variable loads, he can say that it is the best and least expensive device that has come to his notice, and that it has solved the problem of the government of water power under extremely variable loads in the instance herein cited. In his opinion there is no reason existing why water power cannot be successfully employed, where variable loads are the rule, by the use of electric governors. The conditions should be made as favorable as possible in original construction, and the electric principle applied to governing the gates will give satisfactory results in steady power.

## DISCUSSION.

Mr. Hawks. A. McL. HAWKS, JUN. AM. SOC. C. E.—There is a small water power near Olympia, Wash., which is used for milling purposes and also to operate an electric railway and lighting system in that city. The same pair of 60-in. wheels drives the railway and lighting generators, and the result is that the incandescent lamps flicker considerably, owing to the varying loads on the railway circuits. The water is taken directly from the falls and delivered within 50 ft. to the wheels. The ball governor originally tried as a regulator proved to be useless, so the governing is now done by keeping a man all the time at the entrance gate of the penstock. He has before him the voltmeter and ammeter of the circuit and five incandescent lamps, so that his eye will be attracted not only by the swinging of the needles, but also by the flickering of the lamps. As fast as a change occurs the headgate is opened or closed, the governing being done entirely in this manner. The work requires two men, who are paid \$1 50 a day each, making the total expense of this system of governing over \$1 000 a year. The manager of the works is so well satisfied with it that he refused the speaker's offer to supply a reliable governor which would operate automatically, for a sum equal to the semi-annual cost of the present method.

Mr. Smith. J. WALDO SMITH, ASSOC. M. AM. SOC. C. E.—With regard to the statements in the paper concerning the time needed to change the condition of motion in long penstocks, it may be said that observations on a 4-ft. pipe about 22 miles long have shown that a change of conditions at the lower end will affect the flow of water inside the pipe in less than a minute. The water starts and stops almost instantaneously with the opening and closing of the gate.

## CORRESPONDENCE.

Mr. Frizell. J. P. FRIZELL, M. AM. SOC. C. E.—The methods and mechanism described by the author are capable, without doubt, of accomplishing what he claims, and were regulation the only condition to be fulfilled in the use of water power, this would be an advisable method of securing it. Economy in the consumption of water is, however, an indispensable condition in the use of water power, and it appears to the writer that the method described would be attended with very material sacrifices from this point of view.

The regulation of water-wheels by gates placed in the penstock or draft-tube has been adopted and practiced by engineers of standing. The writer has therefore thought it worth while to point out in some detail the nature and extent of the losses involved in such a system.



The wheel is the so-called Victor wheel, a pair of wheels on a horizontal axis. The head is 40 ft., the maximum yield of power 400 effective horse-power, the power in current use varying from that figure to practically nothing. Like all wheels, it is provided with a regulating gate, properly so called. The author introduces an additional gate, which may be called a throttle gate, in the draft-tube below the wheel. The conditions would be precisely the same if it were introduced in the penstock above the wheel. In this arrangement the regulating gate, or gates, of the wheel remains fully open at all times, the mode of regulation consisting in diminishing or increasing, according to requirement, the effective head acting on the wheel. The portion of the head excluded from operation on the wheel is employed in giving velocity to the water after it has passed the wheel. The writer will compare the quantities of water corresponding to different amounts of power in this system with those where the regulator acts on the regulating gate.

The makers of the wheel place the efficiency when running under full gate at 0.81. This is its efficiency under all conditions in the author's system. This fact tends to economy, while the diminution of the head tends in the opposite direction.

The quantity of water required for 400 H.-P. is—

$$\frac{400 \times 550}{40 \times 62.3 \times 0.81} = 109 \text{ cu. ft. per second.}$$

Suppose the requirement for power to be reduced to 300 H.-P. This would be furnished with an efficiency of about 0.77. In this condition the quantity, with regulating gate controlled, would be—

$$q = \frac{300 \times 550}{62.3 \times 40 \times 0.77} = 86 \text{ cu. ft. per second.}$$

To find the quantity corresponding to 300 H.-P. when controlled by throttling the draft tube, it is necessary to proceed as follows:

$q$  = quantity of water discharged, in cubic feet per second.

$h$  = head acting on wheel, in feet.

The two following equations may be written:

$$\frac{0.81 \times 62.3 q h}{550} = 300. \quad (1)$$

$$q = 109 \sqrt{\frac{h}{40}} \quad (2)$$

From which the following are obtained:

$$h = \left( \frac{550 \times 300 \sqrt{40}}{109 \times 62.3 \times 0.81} \right)^2 = 33.02 \dots (3)$$

$$q = 109 \sqrt{\frac{33.02}{40}} = 99 \dots (4)$$

Mr. Frizell. That is to say, to obtain 300 H.-P. by controlling the regulating gate would require 86 cu. ft. per second. To obtain the same power by the author's method would require 99 cu. ft. per second.

Performing the same computations for 250 H.-P., it will be found that this could be obtained by controlling the regulating gate with 78 cu. ft. per second, and by throttling with 93 cu. ft., the effective head in the latter case being 29 ft. With 200 H.-P. the figures would be 70 and 86 cu. ft. respectively, the head in the latter case being 25 ft. With 150 H.-P. the efficiency of the wheel is assumed at 0.50. The quantity in the first mode of regulation would be 66 cu. ft. per second, and in the second 79 cu. ft., with an effective head of 21 ft.

This mode of computation is not strictly correct. To avoid intricacy, the efficiency of the wheel at three-fourths, five-eighths, one-half and other parts of the maximum power has been assumed the same as the efficiency at three-fourths, five-eighths, one-half and other parts of the maximum discharge. A true computation would show the difference in economy between the two modes of regulation to be greater than here appears. It is sufficient, however, to show that regulation by throttling is not advisable where economy in use of water is of importance.

The writer's object in this criticism is simply to point out the inherent and unavoidable defects of the proposed mode of regulation. He will offer one further remark upon the statement quoted from the inventor, viz., "it requires time for gravity to energize or give motion to the increased quantity of water required for an increase of load."

The writer must pronounce this an unqualified error. In a pipe of the length indicated, filled with water under some pressure, if the wheel gate is conceived to be instantaneously opened, the starting of the water through the gateway would be absolutely coincident with the opening of the gate. The entire contents of the pipe would not start simultaneously. A change of pressure in such a condition is propagated through the pipe with the velocity of sound in water; about one-twelfth of a second would elapse from the starting of the gate before the water commenced to move at the receiving end 400 ft. distant. The discharge during this interval would be maintained by the expansion of the water and contraction of the pipe consequent upon the release of pressure.

Mr. Replogle. MARK A. REPLOGLÉ, Esq.—The writer has been making a special study of the problem of governing water power under variable loads for some years past, and has necessarily had some varied experience in this line. He has made a detailed study of the practice of using long closed flumes and penstocks, and, in his opinion, too little attention has been given by engineers to their effects in the matter of government or wheel regulation.

The draft-tube governing appliance referred to in the paper is Mr. Replogle's evidently an expedient to overcome, or partially so, the evil effects of a long horizontal penstock. Water being practically inelastic, it is plain that for every increase or decrease in quantity entering the wheel gates, there must be a corresponding increase or decrease in the rate of flow throughout the flume or penstock. Wheel plants have been designed and built where it requires the full power of the head for many seconds to raise the encased horizontal body of water to the velocity necessary to furnish the power required for an increase of load, such as is required in starting one or more cars on the line; and since the motorman takes the power, rather than leaves an order for it, it must be supplied from the revolving machinery until the gravity effects are available for power purposes at the wheel gates. The result is that the speed will drop until balanced by gravity, which balancing can only be done at the expiration of the time necessary for gravity to impart power enough to the great horizontal mass of water to give it the proper velocity at the wheel gates. A water-wheel receives its power by stopping the water to which gravity has given motion, and the water must enter the wheel at a proper velocity in order to yield its fullest efficiency of power. After increasing the opening of a wheel gate at the end of a long pipe or flume, the first effect is a reduction of the velocity in the ratio that the gate area is increased, and this reduction in velocity is lowering the power effect of the water on the wheel, making the first effect after moving the gates the opposite to that desired. This first bad effect, added to that of lost time in changing the velocity in the closed flumes, makes them very undesirable from a governing point of view.

The writer's experience has led him to believe that the discharge gate described in the paper decreases one-half the time in getting the gravity effects where long flumes must be used, as experience shows that about one-half of the water must pass through the wheel to bring it to speed, while only the latter half must be added to furnish the maximum power. This is accounted for by the changes made in the head, by backing the water up in wheel, and by the fact that a full efficiency cannot be had unless the water enters the wheel at a proper ratio of speed.

The experience gained during the development of a 35-mile electric water-power transmission plant in the Rocky Mountains has gone far toward maturing the writer's views concerning long pipes as feeders to water wheels. In this plant the head is 1 410 ft.; the supply pipe is about 3 800 ft. long and 20 ins. in diameter; the static pressure at the wheel gate is 610 lbs. per square inch. Two safety or relief valves were at first provided near the wheels, to insure safety to the pipe in the event of a sudden stoppage of a wheel-gate opening. Experience showed that there was a possibility of damage even before the inertia

Mr. Replogle. of the relief valve weight could be overcome; it was also noticed that when the relief valve operated properly, it would remain open until the pressure was relieved in its vicinity, then it would close. The decrease of pressure at this point would allow a flow of water toward the relief valve, caused presumably by the elasticity of the pipe, and the valve would open a second time more violently than the first. The commotion in the pipe kept increasing with each succeeding opening, until the valve had to be held down to prevent damage to the pipe. This and subsequent experiences proved to the engineers in charge that it was dangerous to trust to the relief valves for safety; hence they were blocked. All valves were provided at once with threaded stems, so as to require considerable time in opening or closing. Before this provision was made another incident occurred, which was expensive as well as interesting. One of the wheel gates was suddenly opened by accident, and the pressure gauge showed a reduction of several hundred pounds after a very short period of time. This induced the operator to close the gate quickly. It is said that the pressure gauge registered 1 000 lbs. almost immediately. The steel pipe burst at a point 700 ft. above the power-house. This presumably was the meeting point of the water in filling the vacuum caused by opening the gate too suddenly. Several hundred feet of the upper portion of the pipe lay in an almost horizontal position; hence the water contained in it would not start so quickly as the water in the more vertical portions. Immediately after the burst occurred, the horizontal portion of the pipe collapsed, as the water left it through the break 700 ft. below.

No attempt was made to govern this power plant by wheel gates. Tangential wheels with deflecting nozzles were used, and these were deflected by an electric device similar to that described in the paper. It might be added that the water from the deflecting nozzle very quickly cut away the solid granite bottom of the tail-race; plank floor lasted less than twenty minutes, and boiler plate lasted only a few days. At present cast-iron blocks are furnished at intervals of a few weeks each.

A unit of power in this plant consists of a 500 H.-P. tangential wheel attached to the same shaft as the armature of a three-phase dynamo. For assistance in regulation, there is also a flywheel keyed to the same shaft. The shaft at normal speed runs 600 revolutions per minute. The power storage of the revolving parts, at normal speed, is about 9 000 H.-P. for one second of time. This is enough to insure power for the sudden changes in speed, as it will carry an increase of 100 H.-P. nearly four seconds before the speed has dropped 2 per cent. This allows ample time for the governor to shift the nozzle to a point necessary to add the increased power demanded, and prevents unsatisfactory changes in speed. The governor is designed to operate in conjunction with the power storage of the plant.

M. S. PARKER, M. Am. Soc. C. E.—The manager of the electric station, referred to by Mr. Hawks, evidently does not put much faith in the automatic governing of water-wheels. His method of governing wheels, however antiquated, is the only illustration of wheel governing mentioned in the discussion.

Theoretically the author agrees with Mr. Smith and also with Mr. Frizell as to the movement of water in pipes, but in governing water-wheels, from the experience of himself and others with whom he has spoken upon the subject, the use of short penstocks where practicable, and large vents where long penstocks are indispensable, is to be advised. Mr. Frizell is correct in his conclusions as to the lack of economy in the use of water with the throttle gate, as mentioned in connection with the governor described. This, however, is of little importance in the instance cited. There is little storage capacity for impounding water. The daily flow of the river represents the maximum amount of power sold to consumers. In the instance mentioned the company pays for the maximum quantity of power used. Most of the water powers in the northwest are similar to this in lack of storage capacity. The problem to be solved in the case cited was the governing of the wheels, and not economy in the use of water. The water-wheel manufacturers fail to govern the wheel gates satisfactorily for variable loads. The equations given by Mr. Frizell solve the problem of economical use of water, but they do not substitute a governor for the gates of the wheels to control the variable load and realize the economy mentioned. Thus he gets back to the original problem.

As a further example of the government of water power under variable loads the author will give a brief description of the method employed for the control of a large unit of power upon a single shaft. The plant consists of a pair of 57-in. cylinder gate turbine wheels operating under 42-ft. head, running two direct-connected electric generators carrying a load of 9 000 amperes at 180 volts. The conditions are such that the entire load may be suddenly removed from the machines through unforeseen complication of circumstances. To avoid the disaster consequent upon such a condition, the following system for control of the power is in operation: A high-speed engine governor, with an electric connection similar to that described in the paper, Fig. 3, is operated from the wheel shaft. When the shaft exceeds a certain speed, the governor acts automatically, opening a cock in the draft tube, breaking the vacuum and losing thereby 16 ft. of head, acting at the same time to start a small motor used for opening and closing the gates. No time is lost through the attendant not being near to start the motor. The gate being closed, the gear is automatically thrown out. Beside the foregoing precautions, a water coil pipe is connected from the head-race to the tail-race. This coil is of sufficient length to carry off an electrical current equivalent to

Mr. Parker. about 800 H.-P. The current is taken from the main conductor in case of the load being removed as mentioned. These combined precautions for the control of this large unit of power under the conditions in which it is used appear from trial to make the control absolutely safe.